SUBJECT: Discussion of J-2 Specific Impulse Performance Improvements on Mission Planning - Case 103-2

DATE: February 14, 1967

FROM: C. Bendersky

ABSTRACT

This memorandum addresses the importance of J-2 engine performance potential and usefulness in the context of a minimum cost product improvement to the Saturn V launch vehicle.

It is shown the specific impulse will be valuable in any of several missions, including manned Mars flybys, manned orbital, and manned lunar applications. Two major approaches to I_{sp} uprating are discussed: (1) the evolutionary J-2S program, and (2) a "longshot" concept; that of an extendable skirt. Section V, "Concluding Remarks", offers the suggestion to reorient the J-2S to make greater I_{sp} available sooner and test the extendable skirt in an available time slot at AEDC (Arnold Engineering Development Center).

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MEMORANDUM FOR FILE

I. INTRODUCTION

Present approaches to advanced manned missions are based primarily on minimum change (cost) modification to the Saturn V launch vehicle. For example, the proposed manned Mars flyby in Ref. 1 restricts the Saturn V uprating to a product improvement growth version of the S-IC first stage to an MS-IC stage. The MS-IC provides for a F-1 propulsion uprating from 1.52-to-1.80 million lbs-thrust level and a propellant loading increase of 600,000-lbs corresponding to a 20-ft tank extension.

The contents of this memorandum are concerned with the potential performance growth of the LH_2/LO_2 S-II second and S-IVB third stages. Attention is paid primarily to improvements to the J-2 engines leading to specific impulse (I_{sp}) performance uprating and its resulting usefulness in several mission modes.

II. HISTORY

The J-2 engine as presently programmed for Saturn V missions is a gas-generator driven turbopump engine providing 205,000 lbs of thrust at the design mixture ratio (MR) of 5:1 (lbs LO_2/lbs LH_2). The engine has an expansion ratio (ε) of 27.5 and provides a minimum of 426-seconds vacuum specific impulse at the design mixture ratio.

During early trade-off studies, it was shown the trans-lunar injection (TLI) payload could improve by operating the engines in a programmed mixture ratio mode. This is a two-step operation in which the LO_2 flow is scheduled during flight to maintain a 5.5 MR during the early burn time and then 4.5 MR until propellant depletion, all at constant LH_2 flow rate. The engine thrust is increased from 205,000-to-225,000 lbs thrust during the early burn time and similarly decreased in the final step. This mode of operation results in a lower total stage

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specific impulse of about 2 seconds (1/2 per cent), however, the loss of impulse is more than compensated by the reduction of gravity losses. Programmed mixture ratio is particularly effective in the S-II stage operation.

The present control Saturn V TLI weight is of the order of 103,000 lbs; that of the Apollo spacecraft is 98,500 lbs for the lunar landing configuration. Thus, in the immediate past little effort was made by the Apollo program to obtain more engine performance. Product improvement activities have led to the J-2S and J-2X efforts funded as part of the supporting development. The following is a short description of the program objectives and status as obtained from Ref. 2.

> "For the past several years we have been sponsoring the J-2X Experimental Engineering Program as a part of the MSF Supporting Development effort. This J-2X program has had, as its objective, the experimental investigation of a number of features to improve the performance and uprating characteristics of the J-2 engine with the companion goals of reducing engine complexity and cost and improving reliability. A number of these features have been developed sufficiently to the point where they can now be considered for incorporation into the mainstream J-2 engine. MSFC personnel have selected these mature improvements and prepared, in conjunction with the contractor, a tentative plan including scheduling and costing. The resulting simplified engine has been designated the J-2S.
>
> The principal features of the J-2S engine that differentiates it from the present J-2, is the provision of idle-mode operation, the incorporation of a bleed cycle, and a new engine start mechanism. Incorporation of these features will permit: elimination of some of the present engine subsystems; removal of the requirement for thrust chamber preconditioning; incorporation of a reliable triple engine start capability and self-ullaging; and significant reduction of the number and complexity of the engine and stage launch preparation events."

It has been proposed to develop the J-2S as a qualified manrated propulsion system for use in S-II and S-IVB vehicles on later SAA and advanced follow-on missions. A goal has been suggested in Ref. 2 for a December 1970 qualification date. The J-2S as proposed (basic J-2S) would increase the Saturn V TLI by only 1800 lbs. This modest increase is obtained essentially through structural weight reductions, possible elimination of auxiliary propulsion, and increased propellant utilization (reduced engine prechilling). In Ref. 2 it was pointed out that greater TLI could be obtained by deliberate effort using several J-2X options not incorporated into the basic J-2S program proposal. Several of these options, with rough costs, proposed by MSFC are presented in Table 1 taken from Ref. 3. Thus, for an additional 10-to-15 million dollars the TLI can be increased a total of 5,500 lbs and for 15-to-30 million dollars the TLI can be increased a total of 6,900 lbs.

The J-2S I_{sp} performance increase would be obtained by increasing the area ratio from 27.5-to-35 or 40 by "pinching the throat." The thrust chamber, to consume propellants at the same rate, operates at higher chamber pressure (Pc). (Pc is inversely proportional to throat area at constant flow-rate.) The incorporation of the new LH_2 centrifugal pump would allow the engine thrust level to increase 20,000-to-25,00 lbs thrust over the 4.5-to-5.5 mixture ratio range and provides some additional reduction in gravity losses during programmed mixture ratio operation. To this writer's knowledge, the present status of the J-2S program is that the AAP office will consider bearing its financial responsibility.

A. Ancillary Technology (Extendable Nozzle)

A recent Rocketdyne concept (Ref. 4) has been studied which if successful could by itself result in a J-2 engine I_{sp} performance between 455-460 seconds or 7-to-8 percent greater than the present reference levels. The concept consists of deploying an extendable skirt which increases the nozzle area ratio (ε) from 27.5:1 (present J-2) to as large as 200:1. Of several preliminary concepts examined, the favored configuration consisted of a combined gas film, radiation cooled skirt made of either refractory metal or refractory cloth. The film coolant is the turbine exhaust gases. It was (orally) reported that a typical weight penalty was of the order of 300-to-500 lbs. This concept could be quite effective for the single engine installation existing in a S-IVB stage, but would run into geometry limitations for the clustered 5-engine S-II stage. A 7-percent I_{sp} improvement for a fully loaded S-IVB stage could provide a 16,000-lbs TLI payload increase. Rocketdyne is presently experimentally investigating the concept at a lower thrust level. The technology required for material selection and duration capability is being evaluated in a current Air Force Rocket Propulsion Lab (RPL) program in which firings will be made at the 8,000-to-10,000 lbs thrust level in an altitude facility at the Arnold Engineering Development Center (AEDC), Tullahoma, Tenn., during April 1967. This program should be carefully watched for a very cost effective J-2 uprating. If successful, this AEDC program could be the precursor for a family of nozzle extensions which are sterilizable and could be used on most advanced propulsion systems.

III. WHY MORE PAYLOAD?

The J-2S basic program in itself is a worthwhile product improvement program, particularly the option of (pressure fed) idle mode operation. However, recent future mission studies show that the increased TLI option is of more value than increased flexibility. Some of the potential missions are discussed below.

A. Manned Mars Flyby

1. Circular Orbit Assembly (200 nm)

The OMSF "Joint Action Group" study of a 1975 manned Mars flyby (Ref. 1) considered a Mars injection from low circular orbit using either three MS-IVB stages in tandem or three S-IVC stages in tandem. The MS-IVB stage is a minimum change S-IVB with oxygen off-loaded so that 196,000 lbs of usable propellant at a MR=5.0 are available and 19,000 additional lbs of LH_2 are available for boiloff. The hydrogen tank is extended 9 ft to provide the required LH_2 volume. Minor insulation changes together with the boiloff allowance would provide an orbit staytime in excess of 50-hours per stage. Thus, the three propulsion stages must be ripple (salvo) fired to allow satisfactory orbital assembly. The S-IVC concept employs external superinsulation and a new/or separated common bulkhead to extend the orbital staytime to as much as 30 days.

The S-IVB type stages were initially launched to a 100 nm circular orbit. Orbital assembly of the stages was planned for a 200-nm altitude. A LO_2/LH_2 kick stage (19,000 lbs) was to be provided for this purpose.

In the above mission mode, J-2 engine performance upratings could accomplish the following:

1. Eliminate the need for the kick stage;
2. or, be used to extend the required time for ripple firing by providing more LH_2 boiloff capability in both S-IVB dirivative configurations, particularly for the MS-IVB;
3. or, provide for a spacecraft weight increase;
4. or, simply provide more design margin.

2. Elliptical Orbit Assembly

An alternate to circular orbital assembly and injection of the Mars flyby spacecraft is that of "elliptical orbit assembly" (EOS) (Ref. 5). In EOS the spacecraft and propulsion modules are assembled in an elliptical orbit in which the perigee velocity is sufficiently high so that the propulsion module has only to supply a small amount of velocity (5,000-to-8,000 ft/sec). In this mode the spacecraft would be lofted into orbit in two launches (using 3-stage Saturn V's) while a third launch would loft the out-of-orbit propulsion module (O^3P) again on top of a 3-stage Saturn V. The potential value of the approach is threfold:

(a) No SAT V uprating required;

(b) Reduced number of Saturn V launches (4-to-3); and

(c) Reduced facility modifications and operating costs. These are possible as the propulsion module would have "long term" orbital storability of the order of six months rather than one for an S-IVC stage.

Current studies of the Mars flyby spacecraft call for a weight of less than 180,000 lbs. Studies of propulsion modules sized to inject a 180,000 lb spacecraft into a Mars orbit are being conducted at Bellcomm. Preliminary results are depicted in Fig. 1 for a one day and two day elliptical orbit. The propulsion module contained high performance cryogenics (LO_2/LH_2 or LF_2/LH_2) having a specific impulse of 460 seconds, a propellant loading of 0.92 (not including engine weight) and an engine thrust-to-weight of 50. As shown in Fig. 1, the propulsion module weighs 105,000 lbs for the two day period orbit and 118,000 lbs for the one day period orbit. These correspond to a Saturn V TLI capability of 98,500 lbs and 105,000 lbs, respectively. The present Saturn V without any modification (103,000-lbs TLI) can handle the two day period orbit with a 5-percent margin. To provide a similar margin for a one day period ellipse a Saturn V TLI capability of 110,000-lbs is required. This requirement can be satisfied by development of the J-2S with performance options, or with a successful J-2 extendable skirt, both at relatively low cost. It is noteworthy that the MS-IC version of the S-IC stage would provide for about 120,000 TLI at a cost in excess of 500 million dollars (Ref. 6). The J-2 extendible skirt could almost match (119,000 lbs TLI) the MS-IC capability at a fraction of the cost. This latter option could provide proper design margin should the O^3P design parameters of Fig. 1 prove optimistic.

Thus, the development of a high performance J-2 engine would provide sufficient margin to insure that O^3P development costs would be recovered quickly from savings in launch operating cost alone.

5. Earth Orbital Missions

Due to lack of development time an uprated J-2 could probably not impact on the proposed early SAA Programs such as the "Apollo Telescope (ATM)" and the "Airlock-Orbital Workship - Multiple Docking Adapter." However, the increased orbital capability would surely be of great value for the precursor one-to-two year duration manned orbital missions prior to actual manned space explorations. For example, an Uprated SI vehicle containing a 455 second I_{sp} S-IVB stage could result in a 16-percent payload increase to a 100-nm orbit, thereby providing a significant extra capability for resupply missions.

The importance of increased J-2 performance in Saturn V manned synchronous missions is also large. For example, the Douglas Aircraft Company (Ref. 7) states that a Saturn V having a 3-burn S-IVB capability can inject into an equatorial synchronous orbit a gross weight of 98,500, of which for manned missions the discretionary payload would be 22,500 lbs. (The remainder is an earth return CSM and spent S-IVB stage.) A 7-to-8 percent J-2 I_{sp} improvement could increase the discretionary payload of the order of 50-percent to 34,000 lbs.

In a similar mission mode, but unmanned, the discretionary payload is 91,000 lbs. An I_{sp} improvement of 7-8 percent provides a more modest but significant payload increase of 12.6 percent. This order of improvement may be significant for missions such as Project ABLE.

C. Lunar Exploration

The present TLI of 103,000 allows the lunar surface delivery of 12,000-to-12,600 with minimum change to the present Apollo. Saturn V uprating to the order of 120,000-lbs TLI with appropriate modification to the lunar module would increase landed payload by approximately 33 percent. The previous value is probably not maximum if minor modifications to the mission mode are incorporated (i.e., use of S-IVB prcpellants in a third burn for lunar orbital braking).

As statedby NASA/MTL in Ref. 9:

> "Although a 33-percent increase is of great interest and can be reflected in payload capacity, surface mobility or staytime, it does not provide (in itself (sic)) adequate increase to permit a basic change in delivery mode such as direct manned delivery. This delivery mode requires in the order of 150,000-to-160,000 TLI. 120,000 is a step in that direction, however, and is therefore, endorsed."

J-2 performance improvement, plus the MS-IC stage would provide close to 140,000 TLI which approaches MTL's desires for the direct delivery mode.

It is noteworthy that 120,000 TLI would more than satisfy the evolutionary lunar exploration mission modes described in Ref. 9.

V. CONCLUDING REMARKS

The object of the preceding text was to show the utility of increased J-2 specific impulse as applied to product improvement Saturn V vehicles. It was the intent of this writer not to deprecate the J-2S program, but rather to hopefully influence program orientation to a path which could be more usefully incorporated into the Saturn V (and, of course, the Uprated Saturn I) vehicles. The performance options of the J-2S program do not depend upon a series development of the basic J-2S-just as idle mode operation is probably feasible on the existing J-2 engine and does not need the J-2S thrust chamber. Thus, it may be possible to define a work statement that can provide uprated J-2 I_{sp} performance before the basic J-2S simplification features are incorporated.

The prime technique for J-2 I_{sp} improvement is higher area ratio (ε). To increase ε, MSFC has proposed reducing the throat diameter while maintaining the maximum exit dimension. To maintain engine flowrate the chamber pressure must be increased requiring LH_2 pump uprating. The axial pump improvement of Table 1 is not a part of J-2S, but rather is particular to the parent J-2 engine. The more expensive option of Table 1 requires use of a new centrifugal LH_2 pump (J-2X program) of which almost three assemblies are available for test. These "fit" the J-2 plumbing and could be incorporated quickly into a test program designed specifically for performance uprating.

Finally, the "longshot" potential of the extendable nozzle technology in an S-IVB stage should be realized. Granted, there may be development problems, however, the payoff of 16,000 lbs greater TLI without the large cost of a J-2S program should excite the imagination. The evaluation of the concept may prove a problem. As per Ref. 10, the J-4 test facility of AEDC could accommodate a J-2 having an ε of 70, or a J-2S having an ε of 100. It is noteworthy that the J-2S program of Ref. 2 includes AEDC testing. It may be possible to also test extendable skirts during the same occupancy. To demonstrate the full potential (ε = 200) flight testing may be necessary, possibly in conjunction with S-IVB orbital burns. However, a J-2 having an ε = 100 will still provide substantial I_{sp} improvement.

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1013-CB-gdn C. Bendersky

Attachment
(see next page)

Attachment:
References
Table I
Figure I

Copy to
Messrs. W. C. Beckwith - NASA/MTP
J. R. Burke - NASA/MTV
P. E. Culbertson - NASA/MTL
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8. Personal Communication, P. E. Culbertson, NASA Hdq., MTL, November 4, 1966.

9. "Assessment of Manned Lunar Program Options Summary Report", (Task 230), C. Bendersky and D. R. Valley, Bellcomm Inc., (To be issued)

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TABLE I

J-2S & J-2S + OPTIONS - UPRATINGS FOR SATURN V

CONFIGURATION	SAT V TLI Δ PAYLOAD	Δ$ In Millions
1. Basic J-2S	1800 lb	$44.5 FY 68 thru FY 71
2. Performance Options		
a. Pinch Throat ε+35:1 & uprate existing axial fuel pump (Existing ε=27.5:1)	3300 lb	$10-15 20% FY 68, 40% FY 69, 40% FY 70 Plus J-2S Cost Only $2 -$3 for pump balance for retooling, contouring, etc.
b. Pinch Throat ε=40:1 plus New centrifugal pump (J-2X pump)	4700 lb	$15-30 20% FY 68, 40% FY 69, 40% FY 70 Plus J-2S Cost Big cost is new centrifugal pump qualification, etc.
c. Fuel System Mixture Control P.U. valve on H_2 instead of O_2	400 lb	Essentially $0 if you do either 2.a, or 2.b, options.

LUNAR Injection payload increase J-2S + 2a + 2c = 5500 lb

LUNAR Injection payload increase J-2S + 2b + 2c = 6900 lb

Information supplied by telephone from Robert Thompson MSFC (PV&E) requested by Col. Burke-MTV, September 15, 1966.

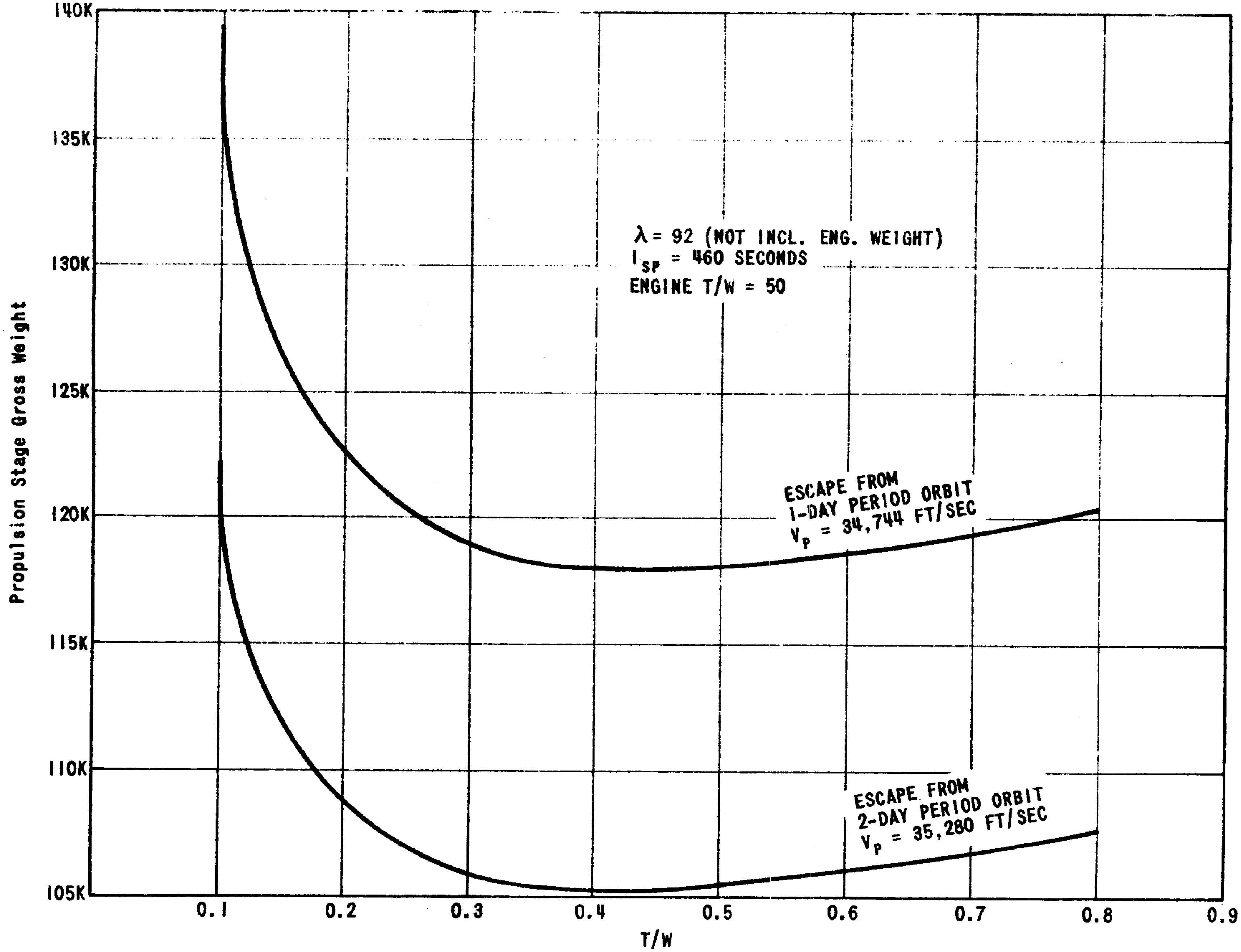

FIGURE 1 - PROPULSION STAGE GROSS WEIGHT VS. T/W RATIO FOR EARTH ESCAPE FROM ELLIPTICAL ORBITS